

AL-TR-1991-0121

AD-A247 825



REFERENCE MODE EFFECT ON THE AUDITORY DISPLAY  
OF AIRCRAFT BANK ANGLE



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February 1992

Final Technical Report for Period 31 August 1990 - 31 August 1991

Approved for public release; distribution is unlimited.

92 3 16 133

92-06852



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This report has been reviewed and is approved for publication.



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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 1992	3. REPORT TYPE AND DATES COVERED Final - 31 Aug 90 - 31 Aug 91		
4. TITLE AND SUBTITLE Reference Mode Effect on the Auditory Display of Aircraft Bank Angle		5. FUNDING NUMBERS C - F33615-89-C-0603 PE - 62202F PR - 7930 TA - 20 WU - 03		
6. AUTHOR(S) Jay C. Neubauer, Don C. Teas, Kent K. Gillingham, Peg Murphy				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) KRUG Life Sciences San Antonio Division P.O. Box 790644 San Antonio, TX 78279-0644		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Armstrong Laboratory Crew Systems Directorate Brooks Air Force Base, TX 78235-5000		10. SPONSORING/MONITORING AGENCY REPORT NUMBER AL-TR-1991-0121		
11. SUPPLEMENTARY NOTES Armstrong Laboratory Technical Monitor: Larry J. Meeker, (512) 536-3337				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This report describes a study which examined flight performance of instrument-rated pilots using only an auditory bank angle display with outside-in and inside-out display reference modes. In Part I, the subjects maintained straight and level flight of the T-40 simulator for 2 min. In Part II, the subjects returned the simulator to straight and level flight from a pseudo-random sequence of preset bank angles. Display reference mode made little difference on performance; however, stimulus factors were found to be important determiners of an auditory frame of reference within which events are placed.				
14. SUBJECT TERMS Auditory Display; Orientation; Flight Performance; Hearing Level			15. NUMBER OF PAGES 36	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

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# REFERENCE MODE EFFECT ON THE AUDITORY DISPLAY OF AIRCRAFT BANK ANGLE

## INTRODUCTION

The United States Air Force's (USAF) concern for maintaining spatial orientation and situational awareness by pilots, along with recent studies in the synthesis of auditory space (33, 34, 35), has led to a renewal of interest in the possibilities for auditory display of information in aircraft. Lyons et al. (24) recently studied auditory cuing as a method for maintaining correct pilot spatial orientation while flying an aircraft, but the use of auditory cuing for orientation is not new. In the 1920s and 1930s, while "blind flying" with instruments was being developed, De Florez (4) proposed and tested his theory that "...the ears are capable of supplanting the eyes in blind flying." De Florez designed and built sound-producing equipment that indicated direction by moving the sound image of a constant-pitch hum from ear to ear and attitude by changing the pitch of the hum. He personally tested the device in ground tests and while blindfolded in flight. After several successful flights and a few modifications, De Florez concluded that blind flight by aural cuing was possible. Some 10 years later, Forbes (10) reported further work to determine the best auditory signal properties, how accurately the signals could be used, and how simultaneous auditory signals might affect performance. Using test subjects in a Link trainer/flight simulator to test various signals, he concluded, "It is possible that auditory signals, if properly designed, can be of assistance in connection with some of the new blind landing systems that are under development." Ford (11) demonstrated that blind landings could be performed with binaural cues for vertical and horizontal deviation from the desired flight path. Ellis et al. (6) also compared visual and auditory cuing during landing. Ellis used sound as an indicator for airspeed during deck landings, and compared this to

the standard dial airspeed indicator and a system of flashing lights. He demonstrated that sound cuing was superior to both the airspeed indicator and flashing light system in helping pilots maintain speed and alignment during a simulated landing task. In their recent study, Lyons et al. (24) used auditory cues for airspeed, vertical velocity and bank angle via an Acoustic Orientation Instrument (AOI) and compared the ability of pilots to maintain a course during simulator flights using visual instruments, auditory cues or both. They concluded that flight oriented by auditory signals was quite feasible.

### Spatial Disorientation

Spatial orientation is based on the evaluation of data from visual, vestibular, and other sensory mechanisms which provide information about motion and position relative to a stationary reference derived from walking upright on hard ground. Auditory and visual events are located by an observer within the orientational space. In an aircraft, the reference is no longer stationary and the evaluation of data from orientation mechanisms may be in error. These errors can lead to responses which, although intended to be corrective, actually are not.

Visual information, for example, may be processed foveally, for recognition and identification of elements, or extrafoveally, for orientation in space. The two visual modes, recognition and guidance, can present conflicting, confusing orientation cues in aircraft (22). False horizons perceived while flying over water at night or over a sloping cloud bank are errors attributable to the guidance mode. Pilots sometimes accept these false cues as veridical and are unaware of the error until the true relation is recognized, perhaps too late. The recognition mode can also produce errors; an example is the size miscue, such as that which results in a high approach to an unusually wide runway. The vestibular and somatosensory systems can give us a false sense of tilt, motion, or lack of motion, producing forms of disorientation called the leans, the graveyard spin, and the graveyard spiral. Inertial forces resulting from linear accelerations in flight produce a resultant gravito-inertial force vector which the pilot may erroneously perceive to be pointing "down." Unfortunately, this resultant vector

can be pointing in any direction, producing a false sense of aircraft attitude, i.e., a somatogravic illusion (14).

Spatial disorientation has been defined as a condition in which a pilot has an orientational illusion, and in which correct orientational information is required to maintain control of an aircraft (14). There are 3 types of spatial disorientation: unrecognized (Type I), recognized (Type II), and incapacitating (Type III). The Type II condition is potentially correctable because the pilot is aware that something is wrong and can "make the instruments read right" to return the aircraft to the proper flight attitude. On the other hand, Type I spatial disorientation is the most common in Class A USAF mishaps according to USAF safety personnel (25), and creates the most concern. The Type III condition is a rare occurrence and contributes to very few mishaps.

Not only is spatial disorientation one of the leading causes of aircraft accidents, it also produces a disproportionate number of fatalities. Epidemiologic studies of USAF aircraft mishaps between 1958 and 1968 identified spatial disorientation as the cause in 6%, but 75% of those accidents were fatal--15% of all fatal accidents were due to disorientation (1). The United States Army reported that 57 of 802 (7.1%) accidents in the year 1966-1967 were orientation-error accidents, and 33.3% were fatal (16). For the year 1969, 7.7% of all United States Navy aircraft accidents were recorded as due to spatial disorientation or were suggested to involve disorientation (31). A greater concern was that 96% of 2,000 Navy pilots surveyed had experienced disorientation in flight (31). In general aviation, the incidence is somewhat less: 2.5% of mishaps (16% of all fatal mishaps) between 1970 and 1975 were caused by spatial disorientation (19).

Another way of assessing the impact of spatial disorientation is by determining the number of aircraft mishaps resulting from "loss of situational awareness," a category that includes the factors of channelized attention, distraction, and task saturation. Clearly, an aircraft flying into the ground because of any of these factors is a consequence of spatial disorientation having occurred during the sequence of events resulting in the mishap. Recent data from the USAF Inspection and Safety Center (12)

reveal that 270 (43%) of the 633 Class A aircraft mishaps that occurred from 1980 through 1989 were categorized as definitely having resulted, or suspected to have resulted, from either loss of situational awareness or spatial disorientation or both. Also, 437 (55%) of the 795 fatalities that resulted were similarly categorized. If only operator-error mishaps are counted, 76% of the mishaps and 85% of the fatalities were due to loss of situational awareness and/or spatial disorientation. Apparently spatial disorientation is a problem that technology has not yet solved. In fact, with faster, quieter, more complex aircraft, the problem may indeed get worse.

As long as there is a good outside visual reference, pilots quickly adapt to the flying environment. Ambient visual cues dominate other, conflicting, cues and strong vestibular and somatosensory inputs usually are suppressed (14). When the outside visual reference is absent, however, other input is required to maintain orientation since the vestibular and somatosensory inputs are not to be trusted. Cockpit instrumentation, in particular, the attitude indicator, provides pilots with an additional visual reference. Pilots probably build their own individual orientation systems through their experience with the visual aids that the cockpit contains. Control of the aircraft through the yoke or stick becomes linked to the visual signals representing the flight parameters. As the signals change, the pilot alters his input to maintain the current orientational objective. Acoustic information might also provide pilots an additional reference for maintaining situational awareness and spatial orientation, particularly in visually deficient conditions.

### Directional Hearing

The ability to locate a sound source in the environment is an extremely important skill for organisms that move. In man the greatest accuracy is in the discrimination of azimuth, and discrimination among elevations requires greater changes in source location (3, 25, 26). In animals for which audition is intimately linked with the detection and recovery of prey, such as bats and owls, there is considerable evidence for neural representation of auditory spatial maps (20, 30). The ears of the owl are not



only on opposite sides of the head but are also displaced vertically and the stimulus differences between the 2 ears vary with elevation as well as azimuth angle. For man it is variation in azimuth angle which produces interaural differences and elevation can be detected monaurally, i.e., the stimulus pairs (right and left) are the same for each elevation. In man and in other species, auditory spatial acuity may be linked with visual spatial assessment. Hearing might be considered an early warning system to alert an organism to the presence and location of a sound source, toward which the animal may turn to make visual identification and subsequent motor response. Studies that reverse the acoustic signals at the 2 ears or that alter the visual signal with prisms show that motor responses to these stimuli come to compensate for the altered stimulus relations.

The stimulus cues upon which the auditory system depends for sound localization can be determined by analytical studies. The interaural differences for sinusoids presented in an echo-free (anechoic) space are limited to amplitude and phase (time). At low frequencies, the interaural amplitude differences are less than at high frequencies since the head provides little shadow for long wavelengths. Above about 3 kHz, however, the head shadow is sufficient to produce an interaural intensity difference (7). Conversely, the delay between the sound at the 2 ears can be resolved by the auditory system for frequencies below about 1.5 kHz. Sinusoids with frequencies between 1.5 and 3.0 kHz are not well localized in anechoic spaces. One would expect that both these stimulus cues would be present for signals with broad bandwidths (5, 21, 28).

Interaural time and intensity differences can be independently controlled by presenting signals through earphones (35). For simple stimuli, like sinusoids, interaural differences in intensity and phase can be synthesized in earphones with simple arrangements; however, such stimuli do not vary simultaneously in elevation. The synthesis of 3-dimensional auditory space requires broad frequency representation (32, 33). With deficient spectral representation auditory space reduces to azimuth only and the source is perceived as an auditory image located inside the listener's head. In this situation, the auditory image is said to be lateralized rather than localized (29).

Recent studies have shown that acoustic signals from the full range of auditory space produce interaural differences in amplitude and phase over a wide range of frequencies (21). Thus, the most effective stimuli for studying localization, or for synthesizing auditory space, are broad-band signals. Brief clicks or white noise can be localized with greater accuracy than sinusoids. The pairs of acoustic power spectra at each ear produced by a broad-band source in auditory space capture all the acoustic cues to its localization that are available. By recalling pairs (for left and right ears) of power spectra (representing many different source locations) from computer memory, converting them to time waveforms, and delivering the waveforms to earphones to reproduce acoustic signals, auditory space has been re-created (32, 33, 34). For example, a sound source may remain in one location as a listener's head moves; however, the spectra of the sounds at the ears change. To synthesize this phenomenon, acoustic waveforms appropriate to the relation between head position and source location must be presented as the head turns.

The pairs of power spectra capture the effects of cancellations and additions of acoustic energy at different frequencies due to reflections from head and shoulders and from the ridges and valleys of the pinnae, for each location of the source. The amplitudes in different frequency regions are modified depending on phase relations of the acoustic reflections from different anatomical regions. These phase relations vary with the position of the sound source. Over a wide frequency range the resulting power spectra may be unique for each pair of ears, but present work suggests that pairs of spectra from an average ear may provide useful data for creating a virtual auditory space. One would expect that the interaural delay for an azimuth location would be most effective for low frequencies and the interaural amplitude differences would be most effective for the high frequencies. One might also expect that their combination, along with the effect of reflections from the head and shoulders, would be required to synthesize the azimuth and elevation of the source.

### Orientation Reference

Since the early days of instrument flight, there has been controversy over how best to present attitude information to the pilot to prevent disorientation when flying without a good outside visual reference. The inside-out display presents aircraft pitch and bank attitude information to the pilot by showing the horizon as it appears when looking at it from inside the aircraft. This convention has been accepted and used almost exclusively in attitude indicator design. Many human factors engineers have questioned the desirability of this reference mode over the outside-in reference mode, which presents aircraft pitch and bank attitude by showing the pilot the aircraft as observed from outside the aircraft. In a review of 270 instrument reading errors, Fitts and Jones noted a small, but potentially very consequential, number of errors due to misinterpretation of the attitude indicator (8). Johnson and Roscoe (17) noted that the cause of 89 aircraft accidents in 1968 was disorientation due to weather conditions. In each case, there was a normally functioning attitude indicator, suggesting that there was either a failure to interpret the attitude indicator correctly or a failure to believe its indication.

Over the past 45 years many studies have tried to resolve the question of whether an inside-out or outside-in display is better. The issue was further complicated when, in 1959, a hybrid display, the Kinalog Display System, was developed (9). In an early study in the mid-1940s, Loucks evaluated pilot performance with various modifications to the standard inside-out attitude indicator and concluded, as a result of his work and earlier work by Browne, that an instrument with a stable horizon and a moving airplane (outside-in instrument) would be more easily interpreted than standard instrumentation (23). In 1954 Browne published further work comparing outside-in and inside-out instrumentation with several modifications (2). He noted that subjects did better with outside-in instrumentation, although experience and increased damping of the inside-out instrument improved performance. While studying relative motion problems associated with air-to-air intercept and air-to-ground missile guidance, Kelley et al. found the outside-in display to be "superior" to the inside-out display (18). On the other hand, Hasbrook and Rasmussen could not demonstrate the superiority of outside-in

instrumentation during in-flight performance testing (15). In addition, Roscoe and Williges found performance with the outside-in display during in-flight trials to be worse than that with other display modes (27). As one might surmise, the question of which display mode is better for the visual attitude indicator remains unanswered.

In this study, we measured the effectiveness of a lateralizing acoustic indicator of bank angle in a USAF T-40 (Link GAT-3) flight simulator. The visually based notion of outside-in and inside-out was imposed on the auditory signal. In the inside-out reference mode, banking the aircraft in one direction is represented on the attitude indicator by a tilt of the horizon in the opposite direction. In an inside-out auditory display, the sound image lateralizes to the ear opposite the direction of bank, just as the horizon moves opposite the direction of bank on the inside-out visual display of aircraft attitude. Conversely, the visual display in an outside-in reference shows the aircraft banking over a stationary horizon. This reference mode is represented in the auditory display by having the sound image lateralize in the direction of the bank, in concert with the actual direction of motion of the aircraft. To simplify the study we chose to look at cuing and performance in only the roll axis. The pilot subjects had only the acoustic information available since the motion base of the simulator was frozen. The subject controlled the simulator from the yoke and attempted to place or maintain the simulator in straight and level flight. Our objective was to determine whether there is a difference in flying performance that can be attributed to display reference mode when an auditory display of aircraft bank angle is used.

## METHODS AND PROCEDURES

### Equipment

The control signals from a USAF T-40 (Link GAT-3) flight simulator were led to an AOI constructed locally (13). The slowly varying analog control signals were smoothed, scaled, and digitized. The 12-bit analog-to-digital (A/D) converter was scaled so that a count of 2,048 represented 30 degrees of bank angle, either left (-) or right (+), around zero degrees of bank angle, which was represented by a count of zero.

The mapped parameters were loaded into a sound generator and timer with an input-output (I/O) port. The outputs from the sound generator were led to an audio mixer/amplifier and then output to earphones wired to accept binaural inputs. The program to map the digitized voltages representing flight parameters into acoustic signals was loaded into the AOI from a computer external to the AOI system.

For bank angle the system controlled the interaural intensity difference of a continuous sound produced by a pulse train. Interaural intensity difference was mapped so that 30 degrees of bank angle presented a maximum intensity difference. (However, even though the intensity difference remained constant, some further alteration in the sound could be detected for bank angles exceeding 30 degrees). Airspeed determined the rate of pulses in the pulse train, which, for this experiment, was maintained at about 1,400 Hz. Small positive and negative peaks on the leading and trailing edges of the pulses indicated some differentiation due to reactance in the overall circuit. Although the signal showed odd harmonics in a spectral analysis, the amplitude of the harmonics fell off rapidly and signal quality resembled that of a sinusoid. For the experiment reported here the other flight parameters displayed by the AOI, i.e., vertical velocity, altitude, and angle of attack, were held constant. [The representation of the various flight parameters presented by the AOI is discussed in Lyons, et al. (24).] The motion base of the T-40 was turned off so that the pilot had no cues of simulated bank angle other than the visual and acoustic indicators.

The sound was presented via earphones. When the simulator was in level flight, the sound image was to be located in the middle of the head since the intensity of the sound at each ear was the same. When the simulator was at some bank angle, the intensity of the sound at one ear was greater than that at the other and the sound image moved toward the ear with the greater intensity. As the bank angle increased, the interaural intensity difference increased. As the subject maintained straight and level flight (Part I), he kept the sound image in the middle of his head. For the restoration of straight and level flight from preset bank angles (Part II), he returned the sound image from a lateral position to the center of the head. The voltage of the control signal for

bank angle from the T-40 was read by a DEC 11-23 computer at each second from the beginning of a trial, converted to bank angle, and stored on disk in files for each trial for each subject. Data were retrieved from these files for subsequent analyses.

### Subjects and Procedures

Twenty pilot volunteers flew the T-40 simulator under our experimental conditions. The range of ages of the subjects was 26 to 51 years. All subjects had approximately 1,000 hours or more of flying experience and were trained in instrument flying. There were 19 males and 1 female. Each pilot had a current Federal Aviation Administration (FAA) medical certificate or Air Force Flying Class II physical. Audiometric data showed an average hearing loss (all subjects) of 3 dB in the left and 2 dB in the right ear for low frequencies (500, 1,000, 2,000 Hz), and 10 dB for left and 5 dB for right ear for high frequencies (3,000, 4,000, 6,000 Hz).

After receiving a full explanation of the experiment, each subject was allowed to practice with the T-40, using both the usual visual information and the auditory signals but with the motion-base off. When the subject became confident in relating the changes in the auditory signal to the visual indicator, the experiment began. The visual flight instruments were covered and a blindfold was placed over the subject's eyes. In Part I the task was to maintain straight and level (S&L) flight for 2 min. Upon completion of the S&L segment, Part II was begun. In Part II the experimenter set the T-40 to the first of a prescribed pseudorandom sequence of bank angles. The sequence was balanced for right and left bank angle for the 3 different angles: 10, 30, and 60 deg. The 20 subjects were randomly assigned to 1 of 2 groups. GP-I received the inside-out display reference mode trials first; GP-O received the outside-in display reference mode trials first. The pseudorandom sequence was different for the 2 groups. For the outside-in display reference mode (O-ref) the subject wore the earphones with the phone marked Right to the right ear. For the inside-out display reference mode (I-ref) the subject put the Right phone to the left ear. For I-ref trials the sound image was lateralized toward the left side for a bank angle to the right. For

the O-ref trials the sound image was lateralized toward the right ear for a bank angle to the right. About 1 h was required for the subject to work through the protocol.

### Data Analysis

Two calculations from the data for the S&L runs are reported: Mean2, the mean bank angle for the second 60 of the 120 samples and EndpointI, the median of the 3 last samples. EndpointII is also reported for the correction from preset bank angles, the second part of the study. In addition, the difference between the bank angle at 1 s and at 2 s (Move1) is reported for Part II. This measure represents an estimate of the direction and magnitude of the subject's correction from the preset bank angles early in his recovery toward straight and level flight. These measures were then studied with the help of analysis of variance (ANOVA) models.

Audiometric data were obtained for all but one subject. The hearing levels were divided into 2 categories, High and Low. The low frequencies were 500, 1,000 and 2,000 Hz. The high frequencies were 3,000, 4,000, and 6,000 Hz. The Hearing Levels (HLs) for the 3 low frequencies were averaged to obtain a single descriptive number as were those for the 3 high frequencies. There were 4 averages for each subject: low and high frequencies for left and right ears. These HLs provided the basis for assigning subjects, post-hoc, to categories, L>R, representing the condition that the loss in the left ear is greater than the loss in the right ear, R>L and R=L. The distribution of these relations was tested with X<sup>2</sup>.

## RESULTS

### Part I: Straight and Level Flight

Two measures of performance, Mean2 and EndpointI, were taken in the S&L segment of the study. Both measures assessed how the subjects used acoustic information to control the simulator. The means for Mean2 and EndpointI are shown in Table 1. Mean2 and EndpointI for the O-ref trials for subjects in GP-I were both statistically different from zero ( $P<0.002$  and  $P<0.023$ , respectively). The GP-I means

for the I-ref trials were similar in magnitude to those for the O-ref trials, but were not significantly different from zero due to variability. No mean for GP-O was significantly different from zero.

Although few statistically significant effects were seen in Table 1, there are consistencies that help interpret data from Part II of the study. There is a bias associated with the display reference mode (I-ref, O-ref) and also one associated with group (GP-I and GP-O). The mean of the I-ref trials is to the right and the mean of the O-ref trials is to the left. Since the display reference mode was changed by reversing the earphone placement, the results suggest a consistent bias due to earphone placement. The direction of bias is the same for the 2 groups, but the magnitude of bias is greater for GP-I than for GP-O. The average absolute bank angle for GP-I is 4.00 degrees, while that for GP-O is 1.24 degrees. Thus, GP-I requires a greater displacement of the attitude indicator to center the auditory image than GP-O.

TABLE 1. AVERAGE BANK ANGLES FOR ESTIMATES OF STRAIGHT AND LEVEL FLIGHT

		I-Ref	O-Ref	
GP-I	<u>PART I</u>			
	MEAN2	5.63	-4.42*	
	ENDPOINTI	4.11	-3.88*	
	<u>PART II</u>			
	ENDPOINTII	4.81	-1.17	
	Average:	4.85	-3.15	Abs.= 4.00
GP-O	<u>PART I</u>			
	MEAN2	1.75	-2.09	
	ENDPOINTI	0.14	-2.30	
	<u>PART II</u>			
	ENDPOINTII	1.74	0.57	
	Average:	1.21	-1.27	Abs.=1.24

\* Statistically Significant



The audiometric data were separated into HLs for Low and High frequencies and for left and right ears. The number of subjects with HL greater in left and right ears and with equal HLs in the 2 ears are shown in Table 2. The average of the HLs for each group are also shown, along with their standard deviations. The only significant features of the HL data were the F-ratios between low frequencies for the 2 groups ( $F=8.04$ ,  $DOF:9,9$ ,  $P<.01$ ) and between the low and high frequencies for each group ( $GP-O:F=20.61$ ,  $DOF:8,8$ ,  $P<.01$  and  $GP-I:F=3.78$ ,  $DOF:9,9$ ,  $P<.05$ ). The F-ratio for high frequencies between the 2 groups was not significant. The magnitude of the average HL for high frequencies was not significantly different between the 2 groups, probably because of the variability in high frequency thresholds.

TABLE 2: INTERAURAL DIFFERENCES IN HEARING LEVEL FOR THE TWO SUBJECT GROUPS

	LOW FREQ'S			HIGH FREQ'S		
	L>R	L=R	L<R	L>R	L=R	L<R
GP-I (n=10)	5	4	1	7	1	2
	Ave. Max. Loss: 3.90 dB			13.50 dB		
	SD:4.11 dB			8.00 dB		
GP-O (n=9)	4	3	2	4	5	0
	Ave. Max. Loss: 2.88 dB			7.22 dB		
	SD:1.45 dB			6.58 dB		

## Part II: Correction from Preset Bank Angle

In the second part of the study, the 3 bank angles (10, 30, and 60 deg) were presented on right and left sides for both the I-ref and O-ref display conditions. The subject restored the attitude indicator to S&L. Move1, taken early in the trial, represents the difference in simulator attitude indicator position between the first and second readings; in essence, it is the magnitude of the subject's initial reaction in restoring S&L flight. The subject concluded each trial by indicating that the simulator was straight and level (S&L). EndpointII is the median value of the last 3 bank angles for each trial.

### Move1

The data were combined in such a way that the effect of bank angle, display reference mode and group could be examined for location of the auditory image. For example, when the display reference mode was inside-out (I-ref trials) and the preset bank angle was to the left, the auditory image was heard on the right side. For the outside-in display (O-ref trials) and preset bank angle to the left, the auditory image was heard on the left side. Figure 1 shows the means for Move1 for each bank angle, for the left and right locations of the auditory image. The 4 curves group into 2 sets, corresponding to the 2 display reference modes, I-ref and O-ref trials.

Three features of the data in Figure 1 are of interest. The first is that the Move1 values for the right and left sides are not symmetrical. One would expect that the lateral position of the auditory image produced by 10 deg to the right would be similar but opposite in direction to that produced by a bank angle of 10 deg to the left. However, for the O-Ref trials, preset bank angles to the right elicited smaller Move1 values than bank angles to the left. For the I-Ref trials, preset bank angles to the left produced larger Move1 values than bank angles to the right. Secondly, Move1 values for the preset bank angle at 60 deg were not very different from those for 30 deg. Thirdly, the Move1 values for GP-O were, in general, larger than those for GP-I for comparable conditions.

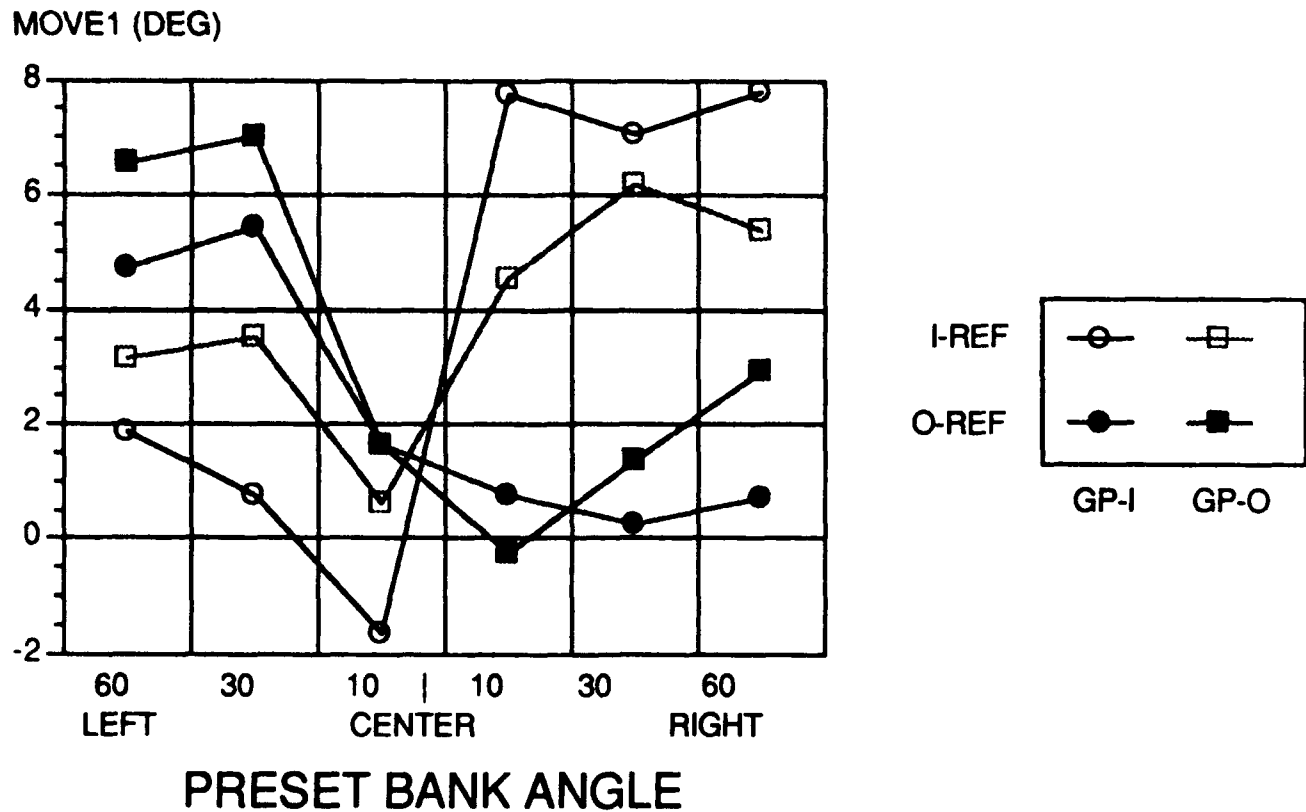
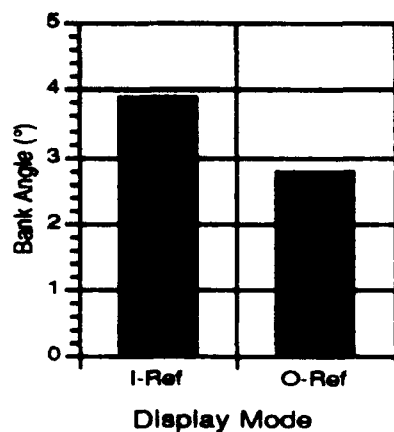


Figure 1. Mean Move1 values for each location of the auditory image.

Figure 2A,B shows the significant main effects for Move1 determined with an ANOVA. Figure 2A shows that the Move1 mean for I-ref trials (inside-out display reference) was significantly greater ( $P < 0.008$ ) than that for the O-ref trials (outside-in display reference). Figure 2B shows that the mean values for Move1 increase as the preset bank angle increases. The differences between Move1 means for bank angles of 10 and 30 degrees and 10 and 60 degrees are statistically significant ( $P < 0.0001$  for each comparison), but not the difference between 30 and 60 degrees.



A

## MOVE1

B

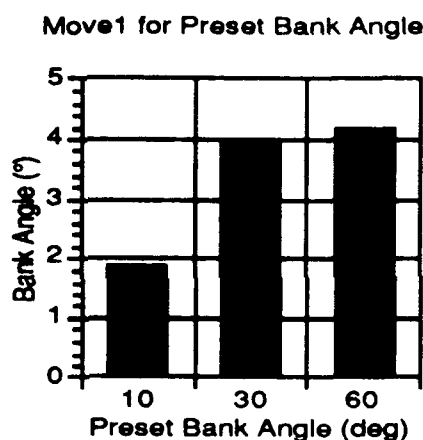


Figure 2. Mean values for the statistically significant main effects ( $\alpha < .05$ ) in the analysis of Move1 (Part II).

The statistically significant interactions in the Move1 data are shown in Figure 3A,B,C. The interaction of image location and preset bank angle was statistically significant (Fig. 3A,  $P < 0.001$ ). The difference between Move1 means (right and left images) for bank angle at 10 degrees was significant, but not the differences at 30 and 60 degrees. There is a highly significant interaction between display reference mode and the location of the auditory image (Fig. 3B,  $P < 0.0001$ ). For the inside-out display reference mode, correction toward S&L for the right-sided auditory image was greater

than that for the left-sided auditory image. For the outside-in display reference mode, the reverse situation obtained.

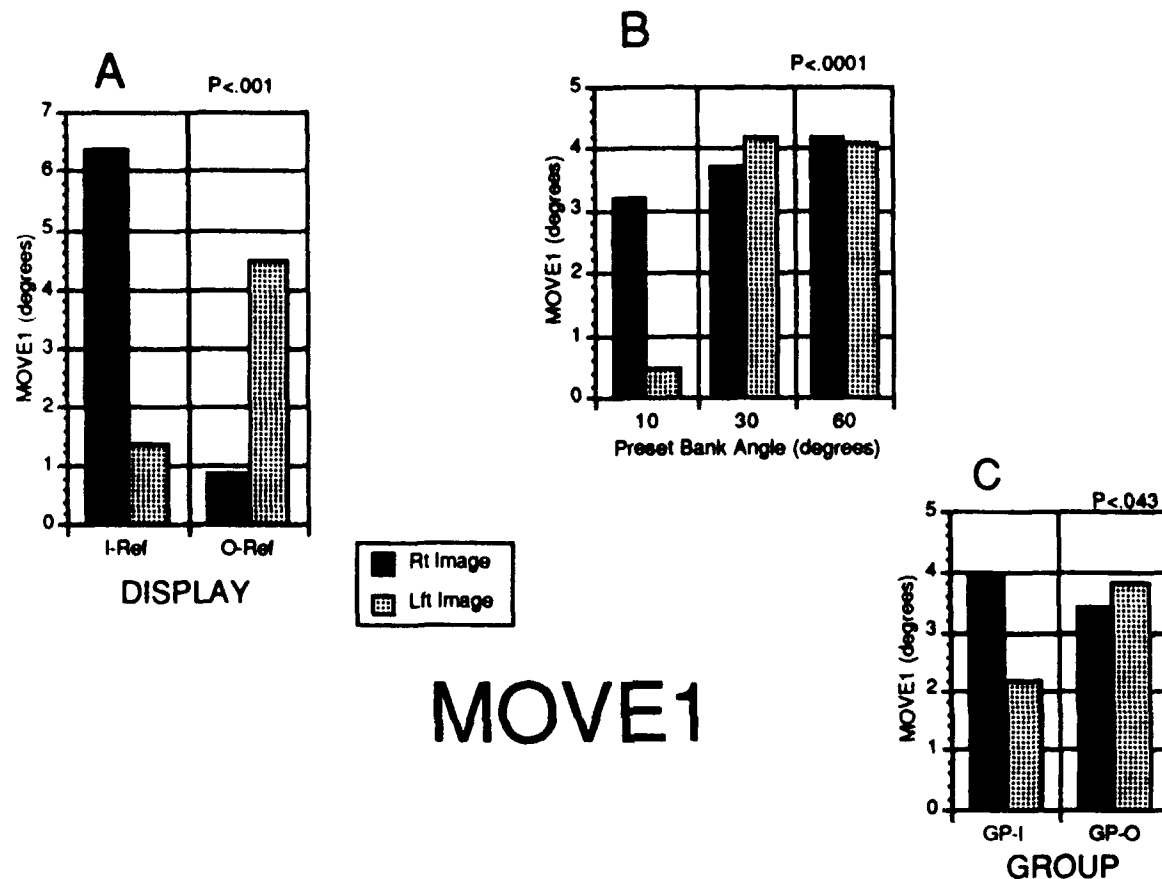


Figure 3. Analysis of MOVE1 Data.

There was also a significant interaction between image location and group (Fig. 3C,  $P < 0.043$ ). The difference in Move1 for the right- and left-sided auditory images for GP-I were significant, but not those for GP-O.

### EndpointII

A significant main effect for EndpointII was found for the display reference mode ( $P < .03$ , Fig. 4A). The mean EndpointII for the inside-out display reference was

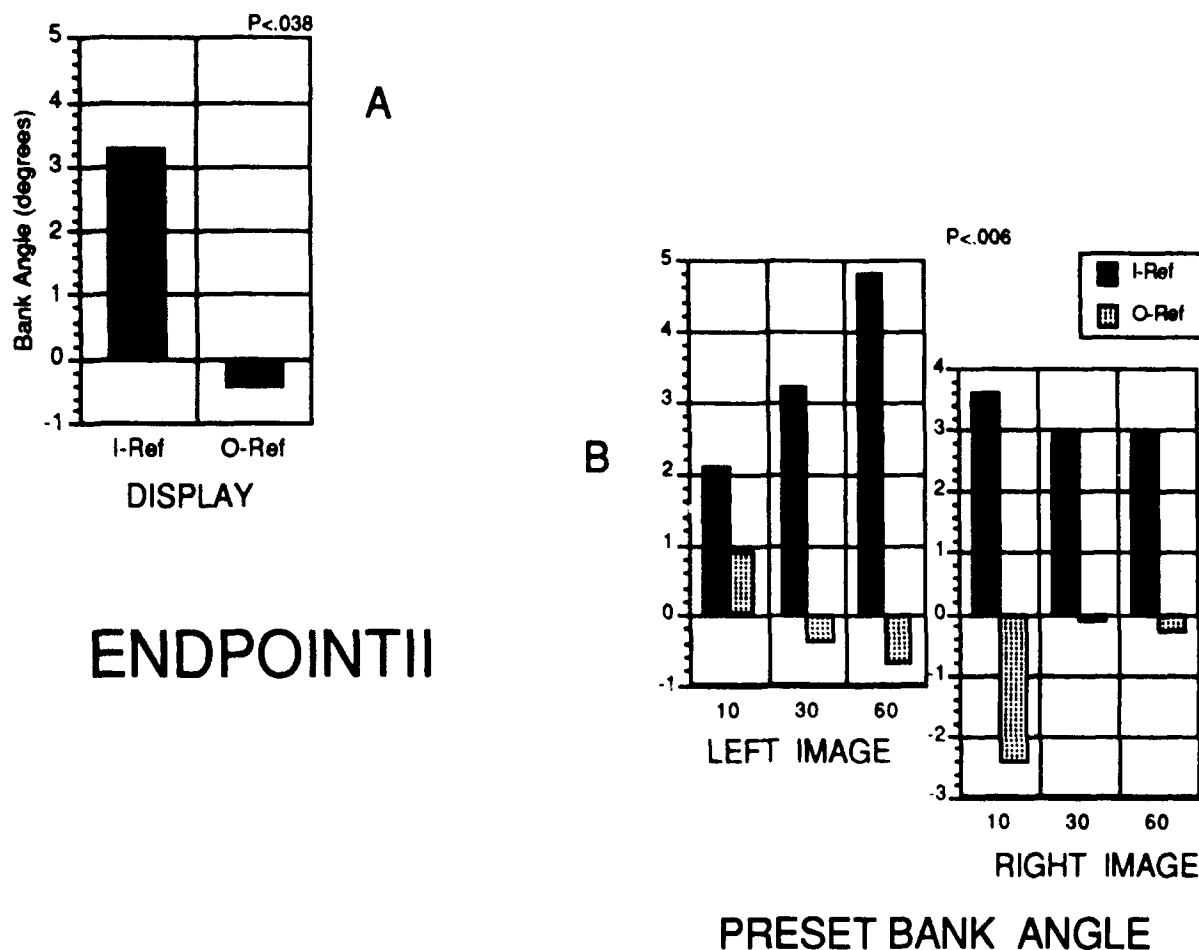


Figure 4. Analysis of ENDPOINTII.

3.3 degrees to the right while that for the outside-in display reference was 0.4 degrees to the left. The 0.4 degrees is not different from 0, i.e., S&L. No other main effect for EndpointII was significant. The 3.3 degrees to the right represents an error in the average subject's estimate of S&L.

Figure 4B shows the mean endpoints of the display reference modes for left and right auditory image locations at the preset bank angles. This 3-factor interaction was significant ( $P < .006$ ). The positive errors for EndpointII for the inside-out display reference mode (I-ref) increase with the magnitude of the preset bank angle for the left-sided auditory image. Overall Mean EndpointII for the outside-in display reference

mode (O-ref trials) was near zero (corresponding to Fig. 4A). However, for the 10-degree bank angle on the right-lateralized image, the error to the left (negative) for the O-ref trials is statistically different from zero.

There was a significant interaction between bank angle and groups for EndpointII ( $P < .027$ , Fig. 5A). The largest difference between the means of the 2 groups occurred at the 30-degree bank angle, with GP-I showing the larger error, 2.4 degrees to the right. Except for the 10-degree bank angle, the error for GP-O was smaller.

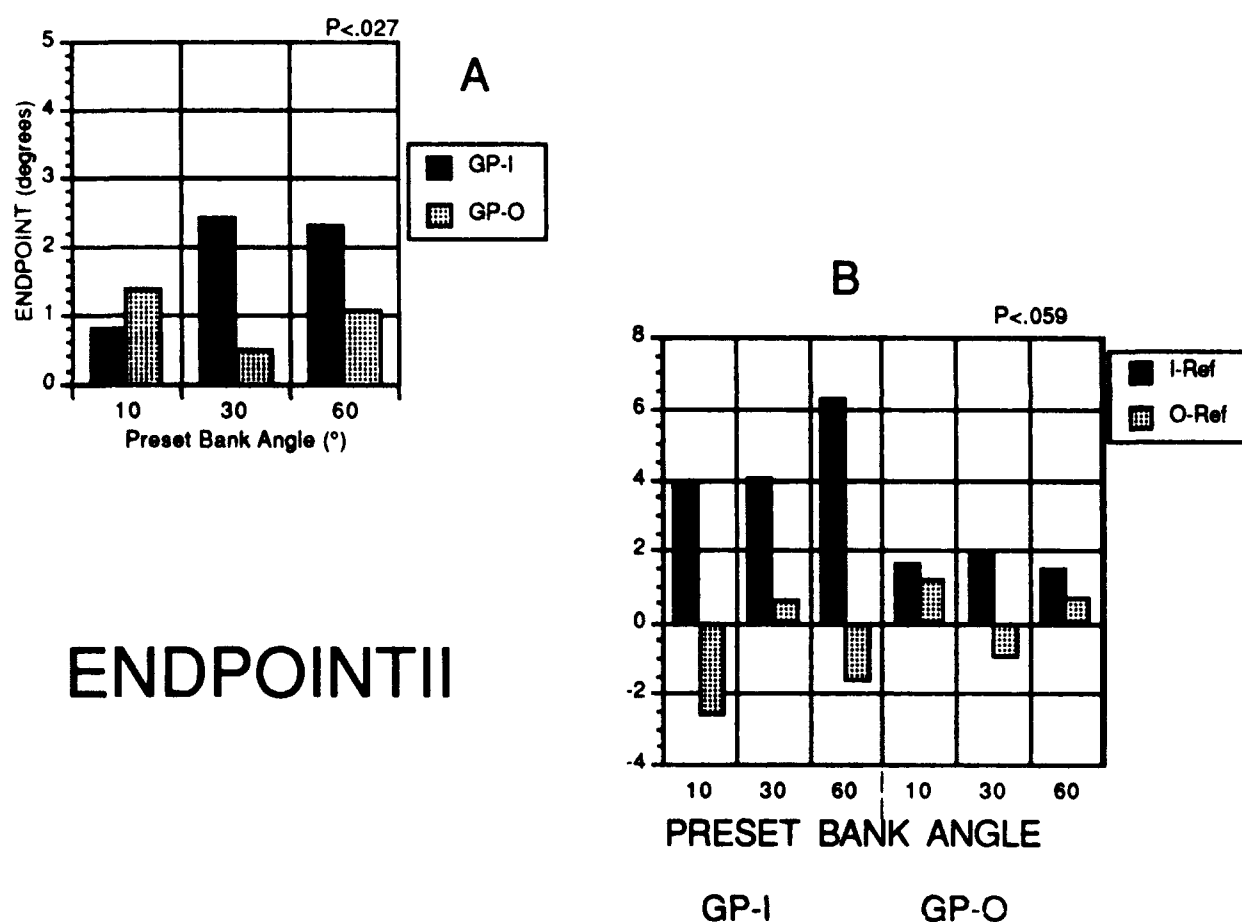


Figure 5. Analysis of ENDPOINTII.

The interaction among group, angle and display reference mode is shown in Figure 5B. This interaction was of borderline significance ( $P = .059$ ). The bias error for GP-I, I-ref trials, was the largest of all, and its direction was to the right. For the

O-ref trials, the bias was to the left, except for the preset angle at 30 degrees. For GP-O, the means are to the right, except for the O-Ref trials at 30 deg.

## DISCUSSION

In Part I of the experiment the subjects' task was to maintain S&L flight for 120 s, using only auditory feedback to control the simulator. In Part II of the experiment the subject returned the simulator to the S&L position from preset bank angles. The mean bank angle for each experimental condition represents the average position of the attitude indicator (available to the subject only in acoustic representation) required to produce an auditory image at the center of the subject's head.

As the bank angle increased, the root-mean-square (rms) voltage at 1 earphone decreased while the voltage to the other earphone remained the same. The auditory image moved toward the side of the earphone with constant voltage. For the outside-in display reference mode, the red earphone was placed on the right ear. For this condition, a bank angle to the right decreased the voltage to the earphone on the left ear and the auditory image moved to the right side. For the inside-out display reference mode, the red earphone was placed on the left ear and a bank angle to the right decreased the voltage at the earphone on the right ear and the auditory image moved to the left side.

There are several possibilities for artifact in binaural studies. Unilateral hearing loss, or an interaural difference in hearing loss, may bias a listener so that the intensity at one ear must be greater than that at the other in order to hear a centered image. Such a listener may report that he has no difficulty localizing sounds in space in everyday activities. When listening to unusual sounds in earphones, however, that subject may show a different response from that of observers without such an interaural difference in hearing loss. If a subject has a loss in, say, the left ear, the intensity at that ear would be made greater than that at the right ear to center the auditory image; i.e., the bias would be in one direction: greater intensity at the left ear, regardless of earphone position.



Another source of artifact is any interaural difference between the acoustic signals which might produce a shift in the auditory image. Suppose that the acoustic input to the right earphone is greater than that to the left. The auditory image will be lateralized to the right. If the earphones are reversed, the image will lateralize to the left, following the stronger acoustic input. Earphone presentation of sounds without visual reference to a source can induce a subject's binaural system to use almost any interaural stimulus difference to produce a favored side. Usually data are combined for right and left sides to balance out the possibility of subtle acoustic artifacts.

The group average for the inside-out display reference mode in Table 1 is positive, i.e., to the right; and that for the outside-in display reference mode is negative, i.e., to the left. The average subject placed the simulator in opposite bank directions for the two display modes in order to center the auditory image. The error to the right for the inside-out display reference mode reduced the voltage delivered to the earphone on the right ear. In this condition, the red earphone is to the left ear. The error to the left for the outside-in display reference mode reduces the voltage to the earphone on the left ear. In this condition, the red phone is to the right ear. Thus, the error follows the direction of the non-red earphone. We infer there is an artifact associated with the non-red earphone channel that biases the judgments. If the error was due entirely to earphone bias, the I-ref and O-ref means should sum to zero. For GP-I, there is a difference between the averages for the 2 display modes of 1.69 degrees to the right. A similar calculation for GP-O shows a difference of 0.06 degrees to the left -- vanishingly small. The magnitude of the bias for GP-I is also larger than for GP-O. Thus, GP-I shows a unidirectional bias in the mean, which suggests that the left ear requires more intensity than the right to center the auditory image. The difference between groups may be related to the greater hearing loss for high frequencies in the left ear among the subjects of GP-I (Table 2). The subjects were assigned to the 2 groups randomly and the HLs were obtained later. The difference between the two groups was unexpected.

In Part II of the experiment the initial correction from preset bank angles, Move1, was analyzed. The relation between Move1 and preset bank angle suggests that the subjects used the lateral position of the auditory image to guide their correction toward S&L and, therefore, must have discriminated the variation in the interaural intensity difference. Interaural intensity differences for lateral positions corresponding to preset bank angles of 10 and 30, or 10 and 60 degrees were discriminated, but not those for 30 and 60 degrees. Although there was a subtle change, perhaps in the timbre of the sound, between the 30 and 60 degree bank angles, the subjects did not appear to use the information. This finding is consistent with the mapping between the range of bank angle of the attitude indicator and the corresponding interaural intensity difference from the AOI. The result verifies that the subjects discriminated the lateral position of the auditory image as it was mapped and used the information about bank angle as they use bank information from the visually assessed attitude indicator.

Since the lateral position of the auditory image increases with preset bank angle one might expect larger Move1 responses for larger bank angles. However, the biases in the estimates of S&L, shown in Table 1, could also affect the image location. The curves in Figure 1 illustrate the effect of the S&L biases on Move1. For the I-ref trials (red phone to left ear) when the image was to the right, Move1 was 5 to 7 degrees; but when the image was on the left, Move 1 was -1 to 2 degrees. When the earphones were reversed for the O-ref trials (red phone to the right ear), Move1 was greater for the left image than for the right image. The data also show that the perceptual center is shifted toward the left by about 10 degrees so that the preset bank angle of 30 degrees, left, is similar in laterality, but opposite in direction, to a preset bank angle of 10 degrees, right. The displacement of phenomenological center produced a distortion so that the preset bank angles extended into auditory space farther to the right than to the left. This distortion can be avoided by having subjects set the earphones to their auditory center prior to using the auditory attitude indicator.

## CONCLUSIONS

1. The data support the findings of Lyons et al. of the possibility that acoustic cuing can be used by pilots for spatial orientation in flight.
2. Factors other than display mode were significant in determining the performance of pilots in maintaining straight and level flight or returning to straight and level flight from different bank angles.
3. When acoustic cuing is restricted -- e.g., to aircraft roll, to interaural intensity differences, and to a tonal signal, as it was in this study -- biases due to imbalances of electro-acoustic channel or the sensitivity of auditory receptors may become prominent.
4. Spectrally rich acoustic signals that incorporate interaural temporal differences as well as intensity differences, i.e., that preserve the stimulus properties associated with localization of sources in auditory space, are required to determine the resolution that the auditory system can provide for spatial orientation.
5. Use of an auditory attitude indicator should be preceded by adjustment to an individual's phenomenological center. This procedure should offset any acoustic effects due to channel differences.

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